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Krishnaswamy

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(54) **BANDWIDTH ADAPTATION IN A WIRELESS NETWORK**

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H04L 12/413 (2006.01)

(52) **U.S. Cl.** **370/310**; 370/445

(58) **Field of Classification Search** 370/310, 370/445

See application file for complete search history.

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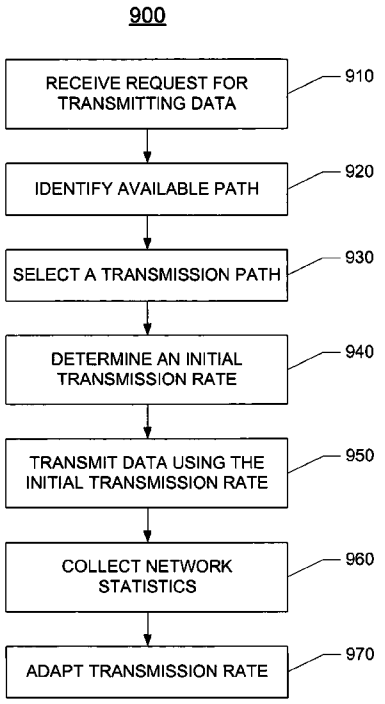
(57) **ABSTRACT**

An arrangement is provided for adapting the output bit rate of a multimedia source to the bandwidth available in a wireless network. Depending on the value of the available network idle time, at least a portion of the available network idle time may be used by the source to increase its output bit rate so that the network bandwidth may be more efficiently utilized. If the effective throughput of the network after the increase of source output bit rate drops significantly, the source may reduce its output bit rate until the effective throughput returns to the level before the source output bit rate increase. Additionally, packet delay and queue jitter information may be collected and used for queue rate adaptation as well as bandwidth adaptation.

21 Claims, 9 Drawing Sheets



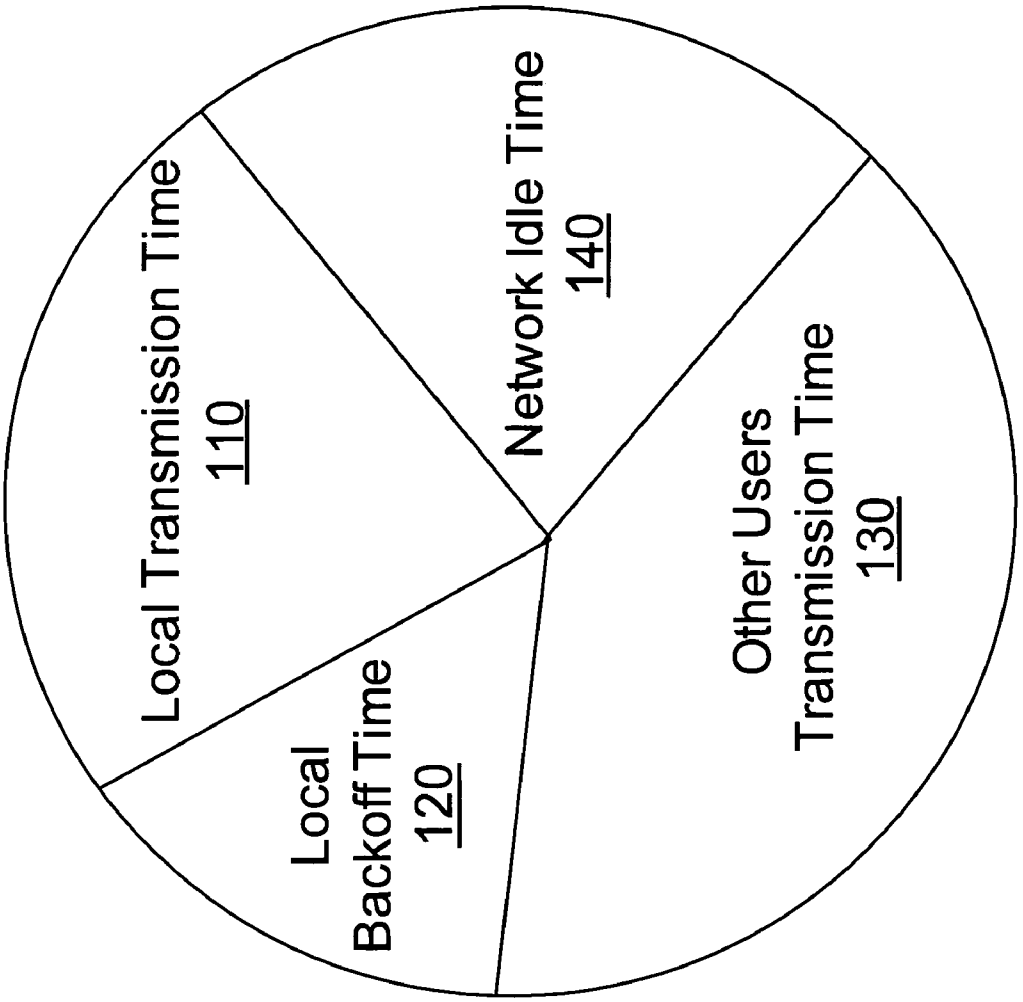

Local Transmission Time
110
Local
Backoff Time
120
Network Idle Time
140
Other Users
Transmission Time
130

FIGURE 1

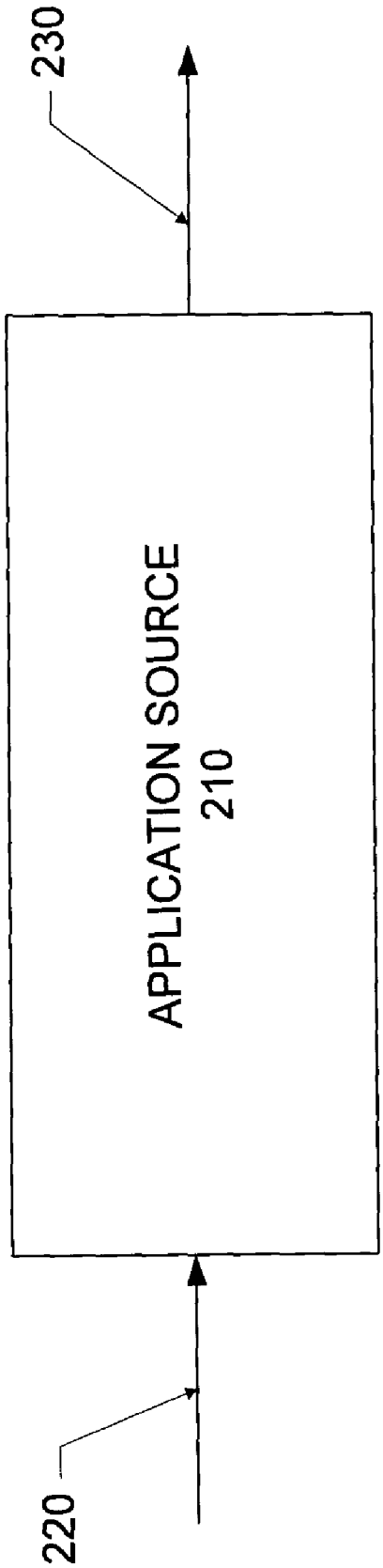


FIGURE 2

```
302:  TxRate = TxBits/measTime ;
304:  ΔTxBits = 0;
306:  If (IdleTime>IdleMinThreshold)
308:          ΔTxBits = ρ * TxBits * [IdleTime / (TxTime + BackoffTime + PacketProcDelay ) ];
310:  else
312:          TxRateDiff = TxRatePrevious – TxRate;
314:          If (TxRateDiff > MinRateDiffThreshold)
316:                  ΔTxBits = - β * MeasTime * TxRateDiff;

318:  ΔTxRate = ΔTxBits/MeasTime;
320:  AvailTxRate = TxRate + ΔTxRate;
322:  TxRatePrevious = TxRate;

324:  TxDelayPrev = TxDelay;
326:  TxDelay = TxQueueDepthInBits/TxRate;
328:  TxJitter = TxDelay – TxDelayPrev;

330:  Perform TxQueueRateAdaptation ();

332:  ReturnToAppLayer(TxRate,AvailTxRate, TxDelay, TxJitter);
```

FIGURE 3

```
410:  TxQueueRateAdaptation()
      {
420:      ForEachPacketInTxQueue
          {
430:          Let S = set of packets in queue ahead of a Packet;
440:          EstimatedPacketDelay = QueueDepthForS /TxRate;
450:          If (EstimatedPacketDelay > AllowedPacketDelay)
              {
460:              If PacketPriorityIsHigh
470:                  DropLowPriorityPacketsInS;
480:              else DropPacket;
              }
          }
      }
```

FIGURE 4

```
502:  IncrementalRateAdaptation() {
504:          TransmitData(SmallInitialTxRate);
506:          ObtainNetworkFeedback(TxRate0, AvailTxRate0);
508:          DiffTxRate0 = AvailTxRate0 - TxRate0;
510:          ChangeTxRate = γ0 * DiffTxRate0;  /* 0 ≤ γ0 ≤ 1 */
512:          AttemptTxRate = TxRate0 + ChangeTxRate0;
514:          TransmitData(AttemptTxRate);
516:          AvailTxRateOld = AvailTxRate0;
518:          ObtainNetworkFeedback(TxRateNew, AvailTxRateNew);
520:          ChangeInTxRate = TxRateNew – TxRate0;
              /* AvailTxRateNew is a function of the available network idle time.
              This idle time can be the idle time as observed at the transmitting
              source node in the wireless network route, or the minimum of the
              idle times of all the sub-networks in the wireless network route. */
522:          While ( (AvailTxRateNew > Delta0)&&(TxRateNew <
                      MaxDesiredTxRate) && (ChangeInTxRate >Delta1) ) {
524:                  DiffTxRateNew = AvailTxRateNew – TxRateNew;
526:                  DiffTxRateUsed = AvailTxRateOld – AvailTxRateNew;
528:                  γ1 = ChangeTxRate / DiffTxRateUsed;
530:                  ChangeTxRate = γ1 * κ * DiffTxRateNew; /* 0 ≤ κ ≤ 1 */
532:                  AttemptTxRate = TxRateNew + ChangeTxRate;
534:                  If (AttemptTxRate > MaxDesiredTxRate) {
536:                          AttemptTxRate = MaxDesiredTxRate;
538:                          ChangeTxRate = ChangeTxRate + (MaxDesiredRate –
                                                 AttemptTxRate);
                      }
540:                  If (ChangeTxRate > Delta1) TransmitData(AttemptTxRate);
542:                  TxRateOld = TxRateNew;
544:                  AvailTxRateOld = AvailTxRateNew;
546:                  ObtainNetworkFeedback(TxRateNew, AvailTxRateNew);
548:                  ChangeInTxRate = TxRateNew – TxRateOld;
              }
      }
```

FIGURE 5

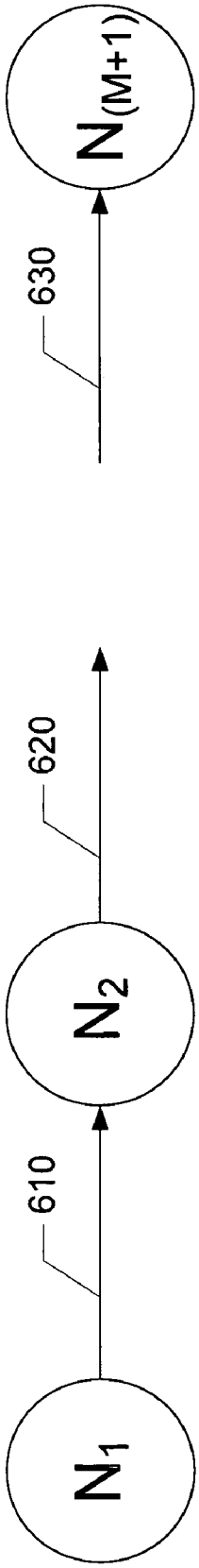


FIGURE 6A

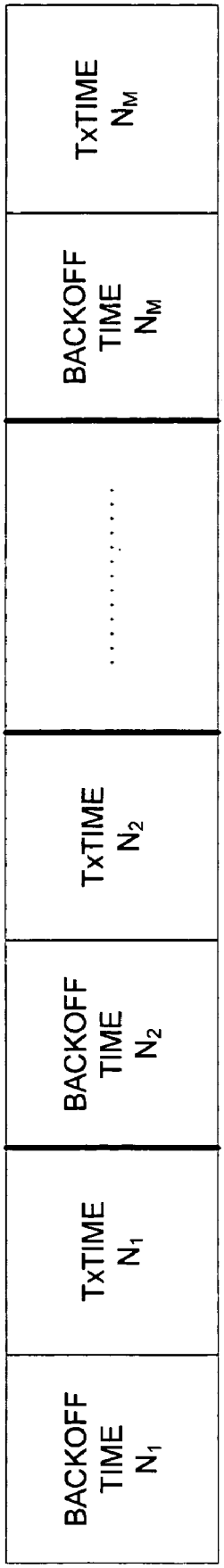


FIGURE 6B

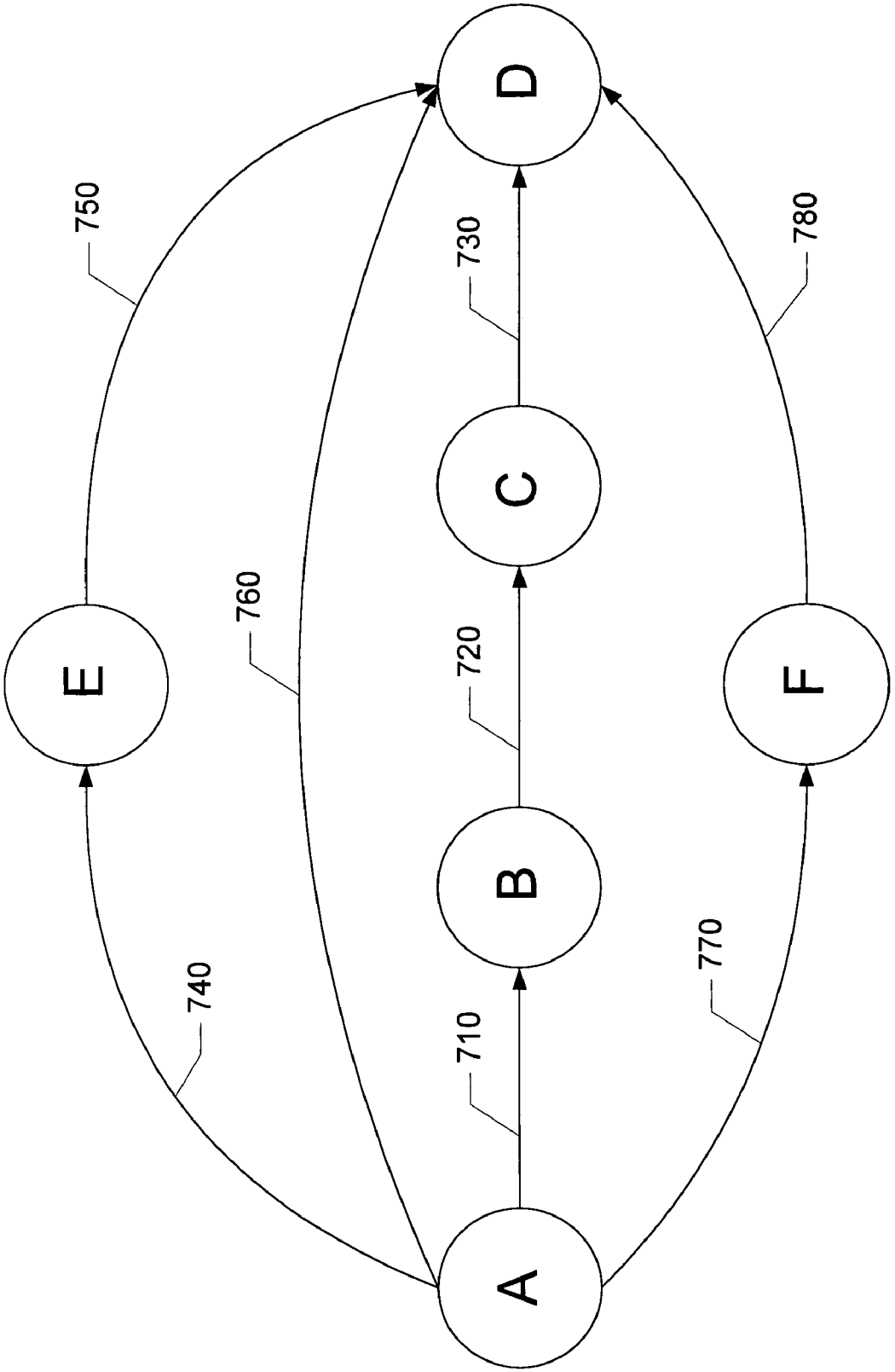


FIGURE 7

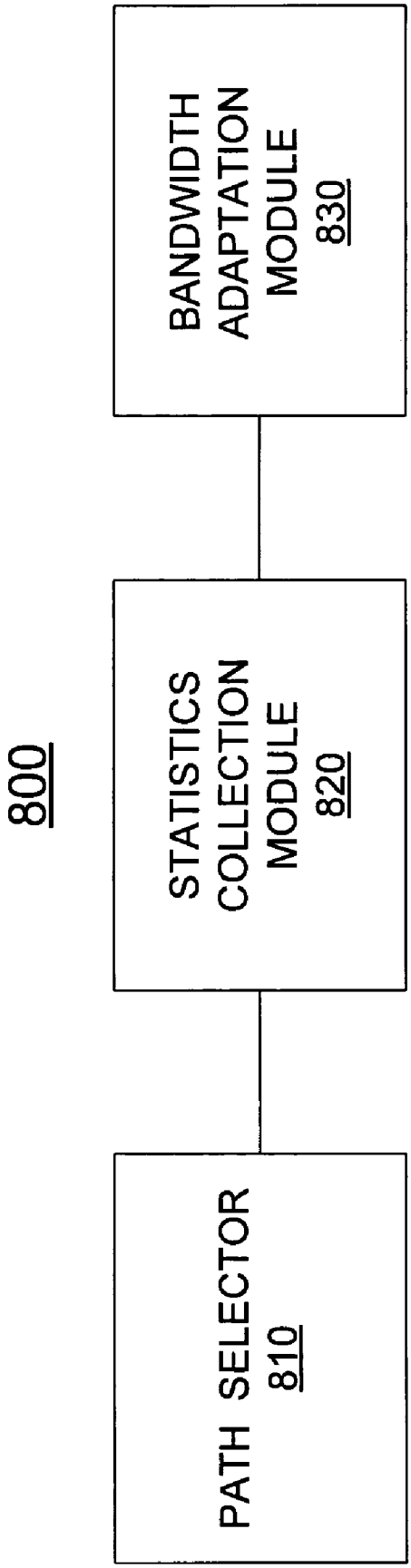

800
PATH SELECTOR
810
STATISTICS
COLLECTION
MODULE
820
BANDWIDTH
ADAPTATION
MODULE
830

FIGURE 8

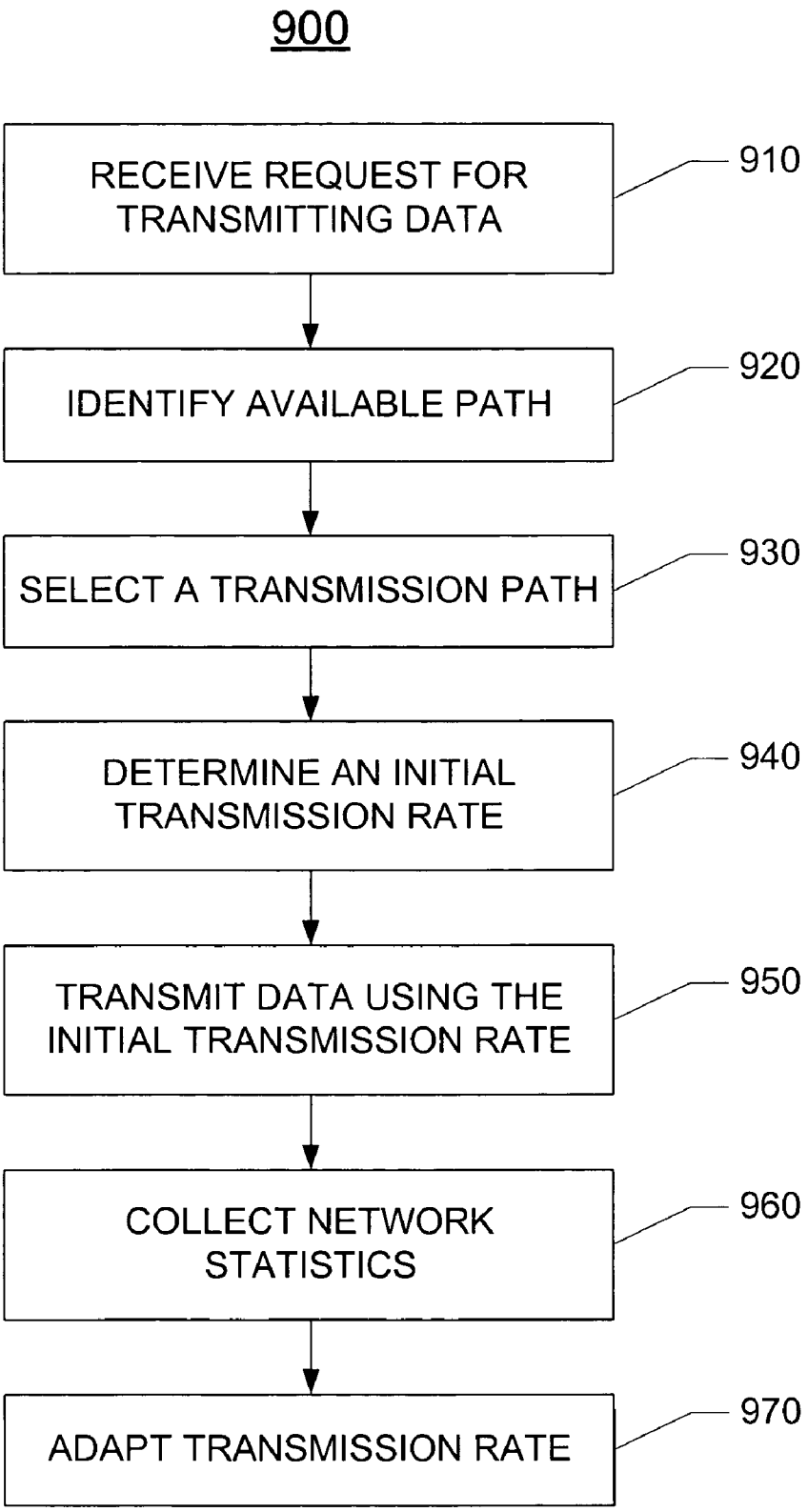

900
RECEIVE REQUEST FOR TRANSMITTING DATA
910
IDENTIFY AVAILABLE PATH
920
SELECT A TRANSMISSION PATH
930
DETERMINE AN INITIAL TRANSMISSION RATE
940
TRANSMIT DATA USING THE INITIAL TRANSMISSION RATE
950
COLLECT NETWORK STATISTICS
960
ADAPT TRANSMISSION RATE
970

FIGURE 9

BANDWIDTH ADAPTATION IN A WIRELESS NETWORK

BACKGROUND

1. Field

This disclosure relates generally to data transmission in a wireless network and, more specifically, to bandwidth adaptation for a multi-media application in a wireless network.

2. Description

In a wireless communication network (e.g., an 802.11 network), a protocol such as a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol) may be used, which may allow only one wireless transmission in progress at a given time in the same channel. Thus, available time on the network may need to be shared between different users active in the network. In addition if there is other unrelated traffic in the network, bandwidth needs to be shared with those traffic components as well. Time utilization with respect to a node in a wireless LAN network can be broken down into several components, one of which is network idle time. The network idle time is perceived by a given node with respect to the wireless medium, during which the given node is neither transmitting nor receiving nor is it in a backoff stage, and nor is any other node transmitting over the medium. It is desirable for an application, e.g., a multimedia application, to adapt its transmitting bit rate to efficiently make use of available time/bandwidth in a wireless network.

BRIEF DESCRIPTION OF THE DRAWINGS

The features and advantages of the disclosed subject matter will become apparent from the following detailed description of the present disclosure in which:

FIG. **1** illustrates an example chart of time utilization distribution in a wireless network;

FIG. **2** is a block diagram illustrating how an application source determines a bit rate for transmitting data in a wireless network;

FIG. **3** is an example pseudo code for bandwidth adaptation based on real-time network statistics in a wireless network;

FIG. **4** is an example pseudo code for transmission queue rate adaptation based on real-time statistics in a wireless network;

FIG. **5** is another example pseudo code for bandwidth adaptation based on real-time network statistics in a wireless network;

FIGS. **6**A-**6**B show a multi-hop transmission path and network time utilization by links in the path in a wireless network;

FIG. **7** is a schematic diagram showing multiple paths between a source node and a destination node in a wireless network;

FIG. **8** is an example block diagram of an apparatus that selects a transmission path, and performs bandwidth adaptation based on real-time network statistics in a wireless network; and

FIG. **9** is a flowchart of one example process for transmitting multimedia data from a source node to a destination node using a real-time network statistics based bandwidth adaptation technology in a wireless network.

DETAILED DESCRIPTION

According to embodiments of disclosed subject matter in the present application, time utilization of a wireless network is monitored and statistics of time distribution are gathered in

real time. Depending on the value of the available network idle time, a portion or all of the available network idle time may be used by an application source to increase its data transmission rate so that the network bandwidth may be more efficiently utilized. Additionally, the effective throughput of the network before and after the application source increases its data transmission rate may be monitored. If the effective throughput of the network consistently drops significantly after the transmission rate increase by the application source, the portion of the available network idle time, which was originally used to transmit more data by the application source, may be reduced until the effective throughput of the network returns to the level before the transmission rate increase by the application source.

Moreover, delay information of packets to be transmitted and jitter information of a packet queue may be measured and used to adapt the transmission data rate by an application source. If an application source transmits data over a multi-link path, link conditions and link utilizations of all the links in the path need to be considered to obtain statistics of idle time, available bandwidth, effective throughput, and others of the network. These statistics may then be used for adapting the transmission data rate of an application source to improve the bandwidth usage of the network.

Reference in the specification to "one embodiment" or "an embodiment" of the disclosed subject matter means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, the appearances of the phrase "in one embodiment" appearing in various places throughout the specification are not necessarily all referring to the same embodiment.

FIG. **1** illustrates an example chart of time utilization distribution in a wireless network. Time utilization with respect to a node in a wireless LAN network can be broken down into several components, e.g., Total time=Local Transmission Time **110**+Local Backoff Time **120**+Other Users Transmissions **130**+Network Idle Time **140**. The local transmission time includes protocol timing overheads and time spent in receiving an acknowledgement. The local backoff time includes the time spent in the random backoff counter prior to transmission. The other users transmissions time include protocol timing overheads for their transmissions and time spent for acknowledgements for their transmissions. The network idle time is perceived by a given node with respect to the wireless medium, during which the given node is neither transmitting nor receiving nor is it in a backoff stage, and nor is any other node transmitting over the medium. For a saturated network with several users, the network idle time may be assumed to tend to 0. However, it is possible that a significant non-zero idle time may be perceived in a saturated network, when no users are transmitting because all users may be in a backoff stage and counting down on their backoff counters.

FIG. **2** is a block diagram illustrating how an application source determines a bit rate for transmitting data in a wireless network. Typically multimedia data (e.g., a video stream) allows for the ability to exploit scalability in different forms such as spatial, temporal and signal-to-noise ration (SNR) scalability. When bandwidth fluctuations occur in a wireless network environment, a multimedia application can be designed to adapt to such changing conditions by monitoring changes in the channel conditions, by exploiting the scalability inherent in the multimedia representation. As shown in FIG. **2**, an application source **210** may produce an output source bit rate **230** ("Sbr") given an input suggested available bandwidth on the network **220** ("Bavail"). It is desirable that

Sbr does not exceed Bavail. The spatial, temporal, and SNR scalability options available in multimedia representation of the application source may be used to scale up or scale down Sbr in response to changing channel conditions in the wireless network.

To efficiently make use of bandwidth resources on a wireless network, it is thus desirable to monitor the appropriate statistics in the wireless network and produce a reasonably accurate estimate of the available bandwidth that can be provided as input to an application source (e.g., **210**). In addition to adapting to available bandwidth in a communication path between two end-points, it is also desirable to ensure that the end-to-end delay constraints for the multimedia application are also satisfied along the chosen communication path.

In one embodiment, network statistics such as local transmission time (TxTime), local backoff time (BackoffTime), network idle time (IdleTime), and packet processing delay (PacketProcDelay) may be measured. Within a period of monitoring time (measTime), one can measure TxTime and BackoffTime associated with all packets (the number of bits transmitted (TxBits)) at the physical layer and/or media access control in the protocol stack. The TxTime refers to both the actual transmission time associated with the packets, and the protocol overhead time such as inter-frame spacing and acknowledgement time, etc. In a wireless local area network ("LAN") with 802.11e priority queues (WMM) enabled, TxTime may be monitored with respect to the packet queue. Once TxTime is obtained, the effective throughput for the traffic may be computed as TxBits/measTime.

The statistic, IdleTime, is an indicator of the network idle time, and not merely idle time for a given node. The IdleTime refers to the time when the local node is neither transmitting nor receiving nor is it in a backoff stage, and nor is any other node transmitting over the medium. Thus, IdleTime refers to the network idle time as perceived at a given node with respect to the wireless medium. If there is IdleTime available during the measTime, such additional time may be used for increasing the bandwidth associated with the multimedia traffic. Since IdleTime measured may not be completely accurate as other users may join the network or attempt to increase their data rates, it may be wise to be gradually opportunistic and request for only a fraction ρ(e.g., $\rho=0.8$) of the available IdleTime on the network, where ρ is a transmission efficiency factor ($0 \leqq \rho \leqq 1$) to account for the fraction of the IdleTime that can be used for increase transmission rate. Assume that remaining transmissions continue at their current utilization levels of the network. If additional multimedia traffic is pumped into the network, it would primarily impact the statistics of TxTime, and BackoffTime for the multimedia traffic, and leave other statistics related to time unchanged. Since TxBits are transmitted in the time (TxTime+BackoffTime), it may be expected that TxBits*ρ*[IdleTime/(TxTime+BackoffTime)] would be the additional bits that may get transmitted in the additional time allocated from the available IdleTime. This assumes that the relative distribution of time between TxTime and BackoffTime remains unchanged. It should be noted that if the perceived available IdleTime is small, it might not be wise to assume that there is additional bandwidth available. This small available value in the IdleTime could be a manifestation of dynamically varying network conditions, or variation in the output of the application source. When it is known that the stream may have to traverse multiple hops, this implies that the available IdleTime needs to be shared across multiple hops, and hence one may have to choose a smaller value of ρ (such as 0.4 for 2 hops) to allocate sufficient time for data transfers on each of the hops.

Additionally, it may be useful to monitor any reduction in effective throughput and to associate such reduction with a drop in the available bandwidth in the network for a multimedia stream based on link adaptation to a lower modulation and coding scheme ("MCS") or additional congestion or interference in the network. Use δ to denote the average difference between Bavail and Sbr. If a drop in available bandwidth is greater than δ, it may be reasonably certain that this loss of bandwidth is not an artifact of the application source producing an output stream that has a low bit rate to begin with. Under such circumstances, it may be wise to throttle back on the estimated bandwidth available on the network to a fraction of its value. By measuring the current and previous values of the effective throughput over two measurement intervals, the difference in throughput values may be estimated. The new value of the available bandwidth can be reduced by a fraction of this observed difference in throughput.

In addition to using the available IdleTime and reduction of effective network throughput for bandwidth adaptation, information of packet delay and packet queue jitter may be used for transmission queue rate adaptation as well as bandwidth adaptation. By monitoring the queue depths of packets related to the multimedia data queue, delay estimates may be obtained. The quantity (measTime−IdleTime) may be used to approximate the total delay in the network to deliver TxBits across the network. If there are QueueBits available in the multimedia data queue, a new packet inserted into the queue has to wait for the QueueBits to be transmitted across the network. Thus, the current delay can be estimated to be given by (QueueBits/TxBits) * (measTime−IdleTime). By averaging the estimates of the current delay over several measurement periods of duration T, one can obtain an estimate for the average delay. By taking the difference in values of the current delay across two measurements, one can obtain an estimate for the perceived instantaneous jitter in the network. By taking the difference in values between the current delay and the average delay, an estimate of the average jitter in the network may be obtained. The packet delay and queue jitter information may be used to decide if any packet in the queue should be dropped. Such information may also be used for bandwidth adaptation. For example, if the delay becomes significantly longer after additional bits being added to the network, the number of the additional bits may be reduced.

FIG. **3** is an example pseudo code for bandwidth adaptation based on real-time network statistics discussed above in a wireless network. Assume that statistics such as TxBits, IdleTime, BackoffTime, PacketProcDelay, packet transmission delay (TxDelay), and transmission queue depth in bits (TxQueueDepthInBits) have been obtained. At line **302**, current transmission rate (TxRate) may be computed. At line **304**, the difference between TxRate before and after bandwidth adaptation, ΔTxBits, may be initialized to zero. At line **306**, a decision whether IdleTime is larger than a threshold, IdleMinThreshold, may be made. The value of IdleMinThreshold may be predetermined according to typical network behavior. Initially, IdleMinThreshold may be set to zero; after several iterations of bandwidth adaptation, it may be found that no benefit may be obtained by using any available IdleTime for transmitting additional data when IdleTime is smaller than a certain value. This certain value may then be used as IdleMinThreshold. If IdleTime is larger than IdleMinThreshold, a portion of IdleTime may be used for data transmission and additional bits to be transmitted may be calculated at line **308**; otherwise, operations from line **312** to line **316** may be performed.

The value of ρ may initially be set to a random value (e.g., 0.8). After several iterations of bandwidth adaptation, it may be found that a certain value or a certain range of values may reflect the network characteristics better than others. Then that value or the average of the range of values may be used for ρ. At line **312**, transmission rate difference (TxRateDiff) may be calculated. At line **314**, a decision whether TxRateDiff is larger than a threshold, MinRateDiffThreshold, may be made. The MinRateDiffThreshold has a positive value and represents a reduction of the network effective throughput. The value of MinRateDiffThreshold may be predetermined based on previous network performance. For example, it may be found that a reduction of the effective throughput within a certain range only represents normal working conditions of the network. The upper limit of that range may then be used as the value of MinRateDiffThreshold. If TxRateDiff is larger than MinRateDiffThreshold, it may suggest that additional bits added to the network are too many and thus require a reduction. At line **316**, such a reduction of additional bits may be computed, where β is a transmission rate reduction factor that can be used to decide how much the transmission rate should be reduced when the effective transmission rate falls below a threshold. It can be set to overcompensate ($\beta>1$) or conservatively compensate ($\beta<1$) as the transmission rate is adapted based on dynamically changing network conditions. The value of β may also be determined randomly and/or according to previous network performance. At line **318**, the change of the transmission rate after bandwidth adaptation, ΔTxRate, may be calculated. At line **320**, available transmission rate after bandwidth adaptation, AvailTxRate, may be obtained. At line **322**, the value of previous TxRate, TxRatePrevious, may be set to the value of the current TxRate.

At line **324**, the value of previous packet transmission delay, TxDelayPrev, may be set to the value of the current packet transmission delay, TxDelay. At line **326**, the value of TxDelay may be updated using the ratio of TxQueueDepthInBits and TxRate. At line **328**, transmission queue jitter, TxJitter, may be computed. At line **330**, an optional transmission queue rate adaptation may be performed. At line **332**, values of TxRate, AvailTxRate, TxDelay, and TxJitter may be returned to the application layer so that the application may use this data to adapt its output bit rate to the available bandwidth of the network. Operations from line **302** to line **332** may be performed at the end of each period of monitoring time, measTime.

FIG. **4** is an example pseudo code for transmission queue rate adaptation based on real-time statistics in a wireless network, which is shown as an operational function at line **330** in FIG. **3**. Line **410** starts the transmission queue rate adaptation function. The function mainly comprises an iteration loop starting from line **420**. The operations inside the iteration loop (i.e., operations from line **430** to line **480**) are performed for each packet in the transmission queue. At line **430**, a set of packets, S, is defined to include all of the packets ahead of the packet at issue. At line **440**, an estimate of delay for this packet, EstimatedPacketDelay, may be computed. At line **450**, a decision whether EstimatedPacketDelay is larger than the value of an allowable packet delay, AllowedPacketDelay, may be made. The value of AllowedPacketDelay may be predetermined based on the requirements of an application/task. If EstimatedPacketDelay is larger than AllowedPacketDelay, the properties of the packet are checked to determine if the packet has a high priority at line **460**. If it does, packets in set S which have lower priority than this packet may be dropped out of the queue at line **470**; otherwise, the packet itself may be dropped out of the queue at line **480**.

FIG. **5** is another example pseudo code for bandwidth adaptation based on real-time network statistics in a wireless network. If the example shown in FIG. **3** is labeled as "one-step" bandwidth adaptation, the example shown in FIG. **5** may be called incremental bandwidth adaptation. The basic idea underlying the example shown in FIG. **5** is that the transmission rate is changed incrementally. This may be done when there is incomplete information about the wireless network and the path taken in the wireless network. It is likely that increasing the application data rate may require the data packets to travel over multiple hops in the network. When the conditions of all the hops are not known but the idle time available in the network is known, one may attempt to slowly increase the data rate in the network. The reduction in the available data rate (which is related to the available network idle time) in response to an incremental change in the data rate is recorded, and the remaining idle time is obtained from the network statistics. Subsequently, the data rate is further increased by larger factors, as more of the network idle time is used up. The incremental rate adaptation is done until further attempts to increase the application data rate fail to cause improvements in the observed application data rate as monitored by the statistics. If the observed application data rate continues to increase, then the application data rate is incrementally increased until the application data rate reaches the maximum value required by the application.

It is possible that in a multi-hop network, the data packets may travel through multiple wireless sub-networks (each sub-network could be an independent or infrastructure basic service set), each of which may have a different amount of idle time. In this case, the adaptation algorithm may need to exploit the minimum available idle time over all the wireless sub-networks. In the adaptation approach shown in FIG. **3**, this minimum available idle time may be needed to take a decision on how to adapt the application data rate. In the absence of information from all of the different sub-networks, the incremental adaptation technique may be used so that small changes in the application data rate may be attempted until further attempts to increase the application data rate do not provide corresponding increases in the observed application data rate over the network. If the observed application data rate continues to increase, the application data rate may be further incrementally increased until the application data rate reaches the maximum value required by the application.

The example pseudo code in FIG. **5** is self-explanatory and incorporated herein as part of the specification.

The principle underlying the bandwidth adaptation schemes discussed above apply to direct transmission paths as well as multi-link transmission paths. Some additional operations may be needed when implementing these bandwidth adaptation schemes for multi-link paths in the same channel. Assume that there are N links of the transmission path in the same channel. In general, it may be necessary to obtain information of the link quality (how fast bits are transferred on a link) and link utilization (how often a link is available for bits to be transferred on the link) for each of the links.

Consider a multi-link one-way transmission path shown in FIG. **6**A with a multimedia transmission source node N_1 and a destination node $N_{(M+1)}$. Assume also that statistics information about each of the M links (e.g., links **610**, **620**, and **630**) is available at the source node N_1. This information may be obtained with the intermediate nodes such as access points monitoring their own statistics and transferred through a

lightweight process to the source node. A mechanism may be required to enable the transfer of information from intermediate nodes to the source node N_1. It should be noted that such an information-transfer overlay mechanism needs to be lightweight and relatively infrequent (typically of the order of a few 100 s of milliseconds for example) so that it consumes very little of the network bandwidth relative to the multimedia data transmissions in the wireless network. Alternatively, the source node N_1, or some other node, may sniff other packets in its neighborhood to get an understanding of the quality of links in its range. When sniffing it should be noted that it is possible that information may be monitored in one direction but not in the other, or on some links but not other links. For example, node N_1 could sniff packets transmitted from N_2 to N_3 but may not be able to sniff information (such as acknowledgements) from N_3 to N_2, or from N_3 to N_4. As more information becomes available, the estimate about link quality and link utilization on each of the links can be improved. Once information about each of the M links is obtained, the end-to-end performance of the wireless multimedia stream may be understood.

If data is flowing in a nice pipelined manner through each of the links, then during a measurement time T, it may be expected that the same number of bits transferred across each link (TxBits). If the multimedia source output is variable bit rate ("VBR") in nature, the measurement time T is assumed to be long enough to average out the variability in the VBR stream. Efficient scheduling of traffic over the multiple links may help with improving the utilization of bandwidth in the network. However, the quality of each of the links may vary depending on the link quality. Some links may require more robust modulation and coding schemes which may take longer to transmit the same amount of data.

FIG. **6**B is an example table showing TxTime and BackoffTime distribution for each of the transmitting nodes as depicted in FIG. **6**A. Once again, it should be noted that this TxTime refers to both the transmission time and the additional protocol overheads such as inter-frame spacing and acknowledgement time for each packet. All of the overheads of retransmission attempts are also included. If there is IdleTime available in the network and it is desired to increase the multimedia source bit rate, then the additional bits added to the network need to travel over each of the links. Assume that TxBits are transmitted over a period of measurement time T, and let TxTotal be the sum of BackoffTime and TxTime over all the links (i.e., $TxTotal=\Sigma_i\ (BackoffTime_i+TxTime_i)$). Then additional bits (AdditionalTxBits) that can be transferred may be given by ρ* TxBits * (IdleTime/TxTotal), where β is a fractional parameter to ensure that the adaptation is gradually opportunistic with a fraction of the available bandwidth being taken by the multimedia stream. If statistics are available for only one link, ρ can be used as a correction factor to account for transmission being required for each of the links. It should also be noted that it is possible that some of the links may be out of range of other links, and transmissions over some links may occur in parallel. In that case, the subset of nodes, which cannot transmit simultaneously due to the nature of the wireless protocol such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and which have the largest combined estimate of TxTotal, should be considered to identify how many additional bits to be transferred.

It is possible that the conditions on one of the links may worsen over time and as a result the throughput of the entire path may drop. In that case, it may be necessary to reduce the Bavail input to the multimedia source as shown in FIG. **2**, with a correction proportional to the difference in throughput. A change to the Bavail input should be made only if there is a significant difference in throughput with respect to multimedia source output variability or small fluctuations in network conditions.

While available IdleTime may be used to increase end-to-end throughput, other options may also be considered for providing positive feedback to increase multimedia transmission bandwidth in the network. For example, if improvements of the link quality are perceivable over the worst link in an end-to-end path, this information may be used to increase the output data bit rate from the source. When sniffing at traffic leaving a node, it is possible to observe changes in the modulation and coding scheme being used with link adaptation at the node by parsing header information, and to observe successful transmissions with the modulation and coding scheme. Information thus observed may be used as an indication of improved link quality. However, some amount of statistics may need to be gathered to correctly estimate improved link quality as a means to improve end-to-end throughput.

The effective end-to-end throughput is reported as the minimum of the effective throughputs over each of the links. The end-to-end delay estimate is a cumulative delay over all the links taking into account the queue depth at each of the links and the corresponding service time in the queue. The end-to-end jitter estimate is also cumulative, noting that contributions to the jitter over some links may be positive and over other links may be negative, based on whether queue depths have increased or decreased in each of the links.

For real-time multimedia transmissions, it is desirable to meet both end-to-end delay requirements and the minimal performance requirements regarding available bandwidth for the application. Multiple paths may be available between two end-points. FIG. **7** is a schematic diagram showing multiple paths between a source node A and a destination node D in a wireless network. There four possible paths between node A and node D: a path including links **740** and **750**, a path including only link **760**, a path including links **710**, **720**, and **730**, and a path including links **770** and **780**. When attempting to choose between alternative paths (e.g., direct or multi-link) with different routes or different number of links, end-to-end delay requirements should be met first. It is possible that links in a multi-hop path may have very good quality, but the overall end-to-end delay may be large due to congestion delays incurred at each link, which cumulatively may make the multi-hop path undesirable. Once the end-to-end delay requirements are met and there are still options to choose between different routes in a wireless network, a path that provides the best end-to-end throughput should become an attractive candidate. In one embodiment, test traffic may be sent along different paths at regular intervals to select the best possible route with the highest reported available transmission rate as conditions dynamically vary.

FIG. **8** is an example block diagram of an apparatus **800** that selects a transmission path, and performs bandwidth adaptation based on real-time network statistics in a wireless network. The apparatus comprises a path selector **810**, a statistics collection module **820**, and a bandwidth adaptation module **830**. The path selector may first identify all possible transmission paths between a source node and a destination node. Second, the path selector may check if all of these possible transmission paths meet the end-to-end delay requirements as determined by an appiication/task, based on network statistics. Only those paths that meet the end-to-end delay requirements become candidate for data transmission from the source node to the destination node. Third, the path selector may select a path among the candidate paths that

provides the best end-to-end throughput for data transmission, based on network statistics. In one embodiment, test traffic may be sent along different paths at regular intervals to select the best possible route with the highest reported available transmission rate as conditions dynamically vary.

Statistics collection module **800** may collect real-time network statistics such as transmission rate, backoff time, idle time, transmission bits during a period of measurement time, packet delay, queue jitter, and so on, for each transmitting node in the transmission path selected by path selector **810**. The statistic collection module periodically collects statistics during a period of measurement time. Bandwidth adaptation module **830** may use real-time network statistics collected by the statistic collection module to adapt the output data bit rate of a multimedia source. The bandwidth adaptation module may use bandwidth adaptation schemes disclosed in this application.

FIG. **9** is a flowchart of one example process **900** for transmitting multimedia data from a source node to a destination node using a real-time network statistics based bandwidth adaptation technology in a wireless network.

At block **910**, a request for transmitting multimedia data from a source node to a destination node may be received. At block **920**, all available paths between the source node and the destination node may be identified. At block **930**, a transmission path among those available paths may be selected for transmitting the multimedia data from the source node to the destination node. The path selection process may involve narrowing those available paths identified at block **920** down to a set of candidate paths by eliminating those paths that cannot meet end-to-end delay requirements as determined by the multimedia source. The path selection process may further involve selecting one path in the set of candidate paths that can provide the best end-to-end throughput. In one embodiment, test traffic may be sent along different paths at regular intervals to select the best possible route with the highest reported available transmission rate as conditions dynamically vary.

At block **940**, an initial transmission rate may be determined partly based on criteria set by the multimedia source (e.g., the maximum time period during which all of the data must be received by the destination node), and partly based on the network characteristics (e.g., channel and protocol used). At block **950**, the multimedia source may use the initial transmission rate to transmit the multimedia data. At block **960**, network statistics, such as transmission rate, backoff time, idle time, transmission bits during a period of measurement time, packet delay, queue jitter, and so on, may be collected for each transmitting node in the selected transmission path. Statistics are collected periodically with each period being a period of measurement time. At block **970**, bandwidth adaptation may be performed based on the collected real-time network statistics.

The bandwidth adaptation process may use those adaptation schemes as disclosed in this application.

Although an example embodiment of the disclosed subject matter is described with reference to block and flow diagrams in FIGS. **1-9**, persons of ordinary skill in the art will readily appreciate that many other methods of implementing the disclosed subject matter may alternatively be used. For example, the order of execution of the blocks in flow diagrams may be changed, and/or some of the blocks in block/flow diagrams described may be changed, eliminated, or combined.

In the preceding description, various aspects of the disclosed subject matter have been described. For purposes of explanation, specific numbers, systems and configurations were set forth in order to provide a thorough understanding of the subject matter. However, it is apparent to one skilled in the art having the benefit of this disclosure that the subject matter may be practiced without the specific details. In other instances, well-known features, components, or modules were omitted, simplified, combined, or split in order not to obscure the disclosed subject matter.

Various embodiments of the disclosed subject matter may be implemented in hardware, firmware, software, or combination thereof, and may be described by reference to or in conjunction with program code, such as instructions, functions, procedures, data structures, logic, application programs, design representations or formats for simulation, emulation, and fabrication of a design, which when accessed by a machine results in the machine performing tasks, defining abstract data types or low-level hardware contexts, or producing a result.

For simulations, program code may represent hardware using a hardware description language or another functional description language which essentially provides a model of how designed hardware is expected to perform. Program code may be assembly or machine language, or data that may be compiled and/or interpreted. Furthermore, it is common in the art to speak of software, in one form or another as taking an action or causing a result. Such expressions are merely a shorthand way of stating execution of program code by a processing system which causes a processor to perform an action or produce a result.

Program code may be stored in, for example, volatile and/or non-volatile memory, such as storage devices and/or an associated machine readable or machine accessible medium including solid-state memory, hard-drives, floppy-disks, optical storage, tapes, flash memory, memory sticks, digital video disks, digital versatile discs (DVDs), etc., as well as more exotic mediums such as machine-accessible biological state preserving storage. A machine readable medium may include any mechanism for storing, transmitting, or receiving information in a form readable by a machine, and the medium may include a tangible medium through which electrical, optical, acoustical or other form of propagated signals or carrier wave encoding the program code may pass, such as antennas, optical fibers, communications interfaces, etc. Program code may be transmitted in the form of packets, serial data, parallel data, propagated signals, etc., and may be used in a compressed or encrypted format.

Program code may be implemented in programs executing on programmable machines such as mobile or stationary computers, personal digital assistants, set top boxes, cellular telephones and pagers, and other electronic devices, each including a processor, volatile and/or non-volatile memory readable by the processor, at least one input device and/or one or more output devices. Program code may be applied to the data entered using the input device to perform the described embodiments and to generate output information. The output information may be applied to one or more output devices. One of ordinary skill in the art may appreciate that embodiments of the disclosed subject matter can be practiced with various computer system configurations, including multiprocessor or multiple-core processor systems, minicomputers, mainframe computers, as well as pervasive or miniature computers or processors that may be embedded into virtually any device. Embodiments of the disclosed subject matter can also be practiced in distributed computing environments where tasks may be performed by remote processing devices that are linked through a communications network.

Although operations may be described as a sequential process, some of the operations may in fact be performed in

parallel, concurrently, and/or in a distributed environment, and with program code stored locally and/or remotely for access by single or multi-processor machines. In addition, in some embodiments the order of operations may be rearranged without departing from the spirit of the disclosed subject matter. Program code may be used by or in conjunction with embedded controllers.

While the disclosed subject matter has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications of the illustrative embodiments, as well as other embodiments of the subject matter, which are apparent to persons skilled in the art to which the disclosed subject matter pertains are deemed to lie within the scope of the disclosed subject matter.

What is claimed is:

1. A method for bandwidth adaptation in a wireless network, comprising:

receiving a request from a source to transmit multimedia data from a source node to a destination node in a packet switched wireless network implementing a collision avoidance protocol allocating wireless transmission times on a wireless channel;

selecting a transmission path for transmission of packets from said source node to said destination node through an intermediate node;

periodically collecting real-time network transmission statistics at the intermediate node, including a network idle time indicator, wherein the network idle time indicator indicates an amount of time when there are no packetized transmissions over said wireless channel detected by the intermediate node and when the intermediate node is not in a wireless transmission backoff stage, wherein timing of the wireless transmission backoff stage is determined by the collision avoidance protocol;

sending the network idle time indicator from the intermediate node to the source node; and

adapting an output bit rate of said source to available bandwidth on said wireless network based on said network idle time indicator and wireless network transmission timing determined by the collision avoidance protocol.

2. The method of claim **1**, wherein selecting a transmission path from said source node to said destination node comprises:

identifying available transmission paths from said source node to said destination node;

selecting a set of candidate paths among said available transmission paths, each candidate path meeting requirements of delay between said source node and said destination node provided by said source ("source end-to-end delay requirement"); and

selecting, in said set of candidate paths, one that provides the highest throughput between said source node and said destination node as said transmission path.

3. The method of claim **2**, further comprising:

determining an initial transmission rate for said source based at least in part on said source end-to-end delay requirements and network characteristics; and

transmitting said multimedia data using said initial transmission rate as the output bit rate of said source.

4. The method of claim **3**, wherein said network characteristics comprise transmission channels and a transmission protocol used by said network.

5. The method of claim **1**, wherein periodically collecting real-time network statistics comprises:

collecting said statistics for a period of measurement time, said statistics including transmission rate, backoff time, the network idle time, transmission bits during said period of measurement time, packet delay, queue jitter for a transmitting node in said transmission path; and

continually repeating said collecting after a time interval until said transmitting node completes transmitting all of said multimedia data.

6. The method of claim **5**, wherein adapting the output bit rate of said source to said available bandwidth is performed after each period of measurement time.

7. The method of claim **5**, wherein adapting the output bit rate of said source to said available bandwidth comprises:

determining said available bandwidth based at least in part on said network idle time; and

increasing said output bit rate by using at least a portion of said network idle time if said network idle time is larger than a predetermined minimum idle time value.

8. The method of claim **7**, further comprising:

monitoring an effective throughput of said network after increasing said output bit rate; and

if said effective throughput drops and the amount of said effective throughput reduction exceeds a predetermined threshold, reducing said output bit rate.

9. The method of claim **8**, wherein adapting the output bit rate of said source to said available bandwidth is performed incrementally.

10. The method of claim **8**, further comprising performing transmission queue rate adaptation after a period of measurement time based at least on packet delay and queue statistics collected during said period of measurement time.

11. An apparatus for performing bandwidth adaptation in a wireless network, comprising:

at least one memory unit;

at least one processor operably coupled to the at least one memory unit, and configured to operably execute instructions associated with a set of modules, including:

a path selector module to select to receive a request from a source to transmit multimedia data from a source node to a destination node and to select a transmission path for transmission of packets between said source node and said destination node through an intermediate node in a packet switched wireless network, the wireless network implementing a collision avoidance protocol allocating wireless transmission times on a wireless channel;

a statistics collection module at the intermediate node to periodically collect real-time network transmission statistics, including a network idle time indicator, wherein the network idle time indicator indicates an amount of time when there are no packetized transmissions over said wireless channel detected by the intermediate node and when the intermediate node is not in a wireless transmission backoff stage, wherein timing of the wireless transmission backoff stage is determined by the collision avoidance protocol, and wherein the statistics collection module is configured to send the network idle time indicator from the intermediate node to the source node; and

a bandwidth adaptation module to adapt an output bit rate of said source to available bandwidth on said wireless network based on said network idle time indicator and wireless network transmission timing determined by the collision avoidance protocol.

12. The apparatus of claim **11**, wherein in selecting a transmission path from said source node to said destination node, said path selector identifies available transmission paths from said source node to said destination node, selects a set of candidate paths among said available transmission paths, each candidate path meeting requirements of delay between

said source node and said destination node provided by said source, and selects, in said set of candidate paths, one that provides the highest throughput between said source node and said destination node as said transmission path.

13. The apparatus of claim **11**, wherein in periodically collecting real-time network statistics, said statistics collection module collects said statistics for a period of measurement time, said statistics including transmission rate, backoff time, the network idle time, transmission bits during said period of measurement time, packet delay, queue jitter for a transmitting node in said transmission path; and continually repeats said collecting after a time interval until said transmitting node completes transmitting all of said multimedia data.

14. The apparatus of claim **13**, wherein said bandwidth adaptation module adapts the output bit rate of said source to said available bandwidth after each period of measurement time, said bandwidth adaptation module determining said available bandwidth based at least in part on said network idle time, increases said output bit rate by using at least a portion of said network idle time if said network idle time is larger than a predetermined minimum idle time value, monitors an effective throughput of said network after increasing said output bit rate, and reduces said output bit rate if said effective throughput drops and the amount of said effective throughput reduction exceeds a predetermined threshold.

15. An article comprising a non-transitory computer readable medium encoded with a computer program, which when executed by a processing platform, cause said processing platform to perform operations comprising:

receiving a request from a source to transmit multimedia data from a source node to a destination node in a packet switched wireless network implementing a collision avoidance protocol allocating wireless transmission times on a wireless channel;

selecting a transmission path for transmission of packets from said source node to said destination node through an intermediate node;

periodically collecting real-time network transmission statistics at the intermediate node, including a network idle time indicator, wherein the network idle time indicator indicates an amount of time when there are no packetized transmissions over said wireless channel detected by the intermediate node and when the intermediate node is not in a wireless transmission backoff stage, wherein timing of the wireless transmission backoff stage is determined by the collision avoidance protocol;

sending the network idle time indicator from the intermediate node to the source node; and

adapting an output bit rate of said source to available bandwidth on said network based on said network idle time indicator and wireless network transmission timing determined by the collision avoidance protocol.

16. The article of claim **15**, wherein selecting a transmission path from said source node to said destination node comprises:

identifying available transmission paths from said source node to said destination node;

selecting a set of candidate paths among said available transmission paths, each candidate path meeting requirements of delay between said source node and said destination node provided by said source ("source end-to-end delay requirement"); and

selecting, in said set of candidate paths, one that provides the highest throughput between said source node and said destination node as said transmission path.

17. The article of claim **16**, wherein said operations further comprise:

determining an initial transmission rate for said source based at least in part on said source end-to-end delay requirements and network characteristics, said network characteristics including transmission channels and a transmission protocol used by said network; and

transmitting said multimedia data using said initial transmission rate as the output bit rate of said source.

18. The article of claim **15**, wherein periodically collecting real-time network statistics comprises:

collecting said statistics for a period of measurement time, said statistics including transmission rate, backoff time, the network idle time, transmission bits during said period of measurement time, packet delay, queue jitter for a transmitting node in said transmission path; and

continually repeating said collecting after a time interval until said transmitting node completes transmitting all of said multimedia data.

19. The article of claim **18**, wherein adapting the output bit rate of said source to said available bandwidth is performed after each period of measurement time, and comprises

determining said available bandwidth based at least in part on said network idle time;

increasing said output bit rate by using at least a portion of said network idle time if said network idle time is larger than a predetermined minimum idle time value;

monitoring an effective throughput of said network after increasing said output bit rate; and

if said effective throughput drops and the amount of said effective throughput reduction exceeds a predetermined threshold, reducing said output bit rate.

20. The article of claim **19**, wherein adapting the output bit rate of said source to said available bandwidth is performed incrementally.

21. The article of claim **19**, wherein said operations further comprises performing transmission queue rate adaptation after a period of measurement time based at least on packet delay and queue statistics collected during said period of measurement time.

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